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Original article

Spreading and evaporation behaviors of adjuvant-amended droplets on different wheat surfaces

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Abstract

Delivering spray droplets to complex, superhydrophobic wheat (*Triticum aestivum* L.) structures, particularly heads and stems, remains a major challenge. Because most studies evaluate flat leaves, this research investigated droplet wetted areas and evaporation time across four wheat surfaces (adaxial/abaxial leaves, stem, head) under varying concentrations of modified seed oil (MSO), non-ionic surfactant (NIS), oil surfactant blend (OSB), and crop oil concentrate (COC). All adjuvants significantly increased spreading but reduced evaporation time compared to water. MSO and NIS maximized wetted areas but dried the fastest, whereas COC exhibited the weakest spreading and the slowest evaporation. A strong negative correlation confirmed a severe thermodynamic trade-off: extensive spreading on highly textured heads and stems created critically thin liquid films that accelerated evaporation. Consequently, maximizing spreading which then risks premature pesticide crystallization. Because interactions are strictly dose-dependent and surface-specific, no universal optimal concentration exists. Agronomists must balance target coverage with droplet longevity through precise adjuvant selection and dosing to ensure maximum biological efficacy.

Keywords: application technology, droplet dynamics, pesticide spray, superhydrophobic surface, *Triticum aestivum* L.

Introduction

Wheat (*Triticum aestivum* L.) is vital to global food security as a primary energy and protein source. Major producers, including the United States and Brazil, have expanded production to meet rising global demand (Alisaac and Mahlein 2023). However, potential yields are continuously threatened by biotic stresses causing major crop losses (Singh *et al.* 2023). The crop is particularly vulnerable to fungal diseases—notably rusts, Fusarium head blight [FHB, *Fusarium graminearum* Schwabe], and wheat blast [*Magnaporthe oryzae* T.T. Hebert] (Figueroa *et al.* 2018), which reduce yields and compromise grain quality through mycotoxin accumulation (Yan *et al.* 2021).

Effective pesticide application in wheat is limited by the difficulty of delivering droplets to non-uniform targets like spikes and narrow leaves (Jørgensen *et al.* 2019; Alisaac and Mahlein 2023; Meng *et al.* 2023). Despite optimized mechanical delivery, proper droplet adhesion and retention require adjuvants (Meng *et al.* 2023). Surfactants and oils reduce surface tension, increase wetted areas, and alter cuticular interactions. This enhances spreading and penetration while managing evaporation to prevent rapid drying or adhesion failure (Yu *et al.*

2009; Gimenes *et al.* 2013). Ultimately, a droplet's fate involves a critical balance between evaporation and tissue absorption (Zhu *et al.* 2008).

Adjuvants optimize spray performance by increasing wetted areas and modulating evaporation (Jiang *et al.* 2024; Meng *et al.* 2025). However, evaluations of how adjuvant classes and concentrations affect droplet dynamics on distinct wheat surfaces remain limited (Precipito *et al.* 2018; Ma *et al.* 2024; Meng *et al.* 2025). Because wheat surfaces are frequently superhydrophobic, water droplets may roll off or fail to adhere adequately without proper chemical modification. Furthermore, these interactions often exhibit a strong concentration-response behavior, where improper dosing can lead to excessive run-off and environmental waste (Gimenes *et al.* 2013; Song *et al.* 2022; Meng *et al.* 2023).

Most droplet deposition studies use flat, horizontal leaf models, neglecting complex, vertically oriented, and superhydrophobic wheat structures like heads and stems. In the present study it was hypothesized that while vegetable-derived oils and non-ionic surfactants overcome epicuticular waxes to maximize spreading, this extensive coverage triggers a thermodynamic trade-off, exponentially accelerating evaporation on these highly textured surfaces.

Thus, the objective of this research was to evaluate the concentration-response behavior of different adjuvant classes (MSO, NIS, OSB, and COC) on wetted areas and evaporation time across four distinct wheat structures (adaxial leaf, abaxial leaf, stem, and head) using an environment-controlled single droplet system. In this study, the droplet wetted area (or dispersion area) was defined as the maximum contact area between the droplet and the target surface after the droplet was deposited and spread on the surface. Evaporation time was defined as the time elapsed from droplet deposition until the water portion completely disappeared from the target surface.

Materials and Methods

Droplet wetted areas and evaporation times were measured using an environment-controlled single droplet system (Zhu *et al.* 2008). A microprocessor-timed fluid dispenser (Model 2405, EFD Inc., East Providence, RI, USA) generated 300 μm diameter spherical droplets, representing a typical agricultural Volume Median Diameter (VMD) that balances target coverage with drift reduction. Target structures were placed in a chamber maintained at $25 \pm 1^\circ\text{C}$ and $60 \pm 3\%$ relative humidity, simulating typical microclimates during wheat flowering (Feekes 10.5). Single droplets were dispensed onto the surfaces while a stereomicroscope coupled with a digital camera captured the spreading and evaporation processes at 1 s intervals.

Evaporation time was determined from image sequences from droplet deposition to complete drying. The wetted area was measured using the polygonal hand-trace tool in ImageProPlus (v4.1, Media Cybernetics, Bethesda, MD, USA), calibrated with a Zeiss 0.01 mm micrometer slide.

Spray solutions were prepared by mixing four adjuvants, crop oil concentrate (COC), modified seed oil (MSO), non-ionic surfactant (NIS), and an oil surfactant blend (OSB) (Wilbur-Ellis Co., San Francisco, CA, USA), with distilled water at five relative concentrations (RC: 0.25, 0.50, 1.00, 1.50, and 2.00) (Table 1). RC was defined as the actual concentration divided by the manufacturer-recommended rate (RC = 1.00 representing the baseline). Distilled water was used as the carrier and control to isolate fundamental adjuvant physical dynamics and avoid confounding interactions with pesticide formulation additives. Adjuvant compositions and solution surface tensions are detailed in Table 1.

The wheat (*Triticum aestivum* L.) variety used for the test was Hopewell. Plants were grown and evaluated at the reproductive growth stage (Feekes 10.5), which is the stage recommended for fungicide applications against critical pathogens. Four locations on the wheat plant surface were selected for droplet placement: the flag leaf (adaxial and abaxial surfaces), the head, and the stem (Fig. 1; Fig. 2). These target locations represented the surface structures most susceptible to infection by pathogens such as *Fusarium* head blight (FHB) and stem rust (caused by *Puccinia graminis* Pers.). Each test was repeated five times.

Data were analyzed using a factorial ANOVA within a general linear model evaluating plant surfaces (four levels), adjuvants (four levels), concentration (five levels), and all interactions. Concentration was modeled quadratically to account for non-linear dose-response behaviors, such as saturation limits. Because three-way interactions (surface $\times$ adjuvant $\times$ concentration) were significant, independent quadratic regressions were fitted for each surface-adjuvant combination, extracting coefficients, standard errors, p -values, and R^2 . Water-only controls were compared against adjuvant treatments using Dunnett's test.

To summarize cumulative dose-response behaviors, the area under the curve (AUC) for wetted areas and evaporation time was computed via trapezoidal integration using the `trapz(x, y)` function in the R 'pracma' package. Here, x represented concentration (% v/v), excluding the 0% water control, and y represented the measured variable. AUC distributions were visualized using box plots. Analyses were performed in R version 4.2.1 (R Core Team 2022).

Results

Wetted areas

Fig. 3 shows 300 μm droplet deposit patterns (water and adjuvants at 1.00 RC) on adaxial surfaces. Wetted areas varied significantly across treatments, surfaces, concentrations, and their interactions ($p < 0.001$). While water droplets covered only 0.19 mm^2 (head) to 0.47 mm^2 (adaxial leaves), adjuvants significantly increased spreading (Fig. 4), ranging from 0.50 mm^2 (COC, abaxial) to 1.80 mm^2 (COC, adaxial). Overall, MSO and NIS generated the greatest increases in wetted areas, followed by OSB and COC. [Insert Fig. 3 here] [Insert Fig. 4 here]

The concentration-response AUC in Fig. 5 clearly showed differences in cumulative wetted areas across five concentrations at different locations on wheat surfaces. For all locations, the wheat head and the adaxial leaf regions displayed the largest AUC values, reflecting their highest overall responsiveness to the adjuvant concentration, whereas the abaxial surface showed the lowest cumulative wettability.

Furthermore, concentration-response relationships for wetted areas varied markedly and exhibited a significant quadratic function with RC across surface and adjuvant combinations (Fig. 6). For instance, on the abaxial and head surfaces, MSO and OSB displayed quadratic functions with RCs characterized by clear peak responses (inverse-U patterns). This interaction was highly dose-dependent.

Evaporation time

Evaporation times of 300 μm droplets varied across targets and treatments. All adjuvants significantly accelerated drying compared to water (Fig. 7). While water droplets evaporated between 140 s (adaxial leaf) and 239 s (head), adding adjuvants at 1.00 RC reduced times to between 69 s (OSB, adaxial) and 146 s (COC, adaxial). OSB and NIS produced the greatest reductions, followed by MSO and COC.

Evaporation time consistently decreased as adjuvant concentration increased (Fig. 8). Adaxially, MSO, NIS, and OSB exhibited strong negative linear effects, whereas COC showed no significant effect. Abaxially, COC and MSO displayed negative linear trends, while OSB produced a U-shaped quadratic pattern. These concentration-response behaviors were adequately captured with high model fits ($R^2 = 0.86\text{--}0.99$).

Area under the curve (AUC) analysis (Fig. 9) confirmed distinct cumulative drying patterns. OSB and NIS exhibited the lowest AUC values (fastest drying), whereas MSO and COC produced higher AUCs (slower evaporation). Leaf surfaces showed the greatest differences between adjuvants. Conversely, the stem displayed narrow AUC distributions,

indicating uniform drying regardless of treatment. Overall, COC showed weaker slopes and smaller evaporation reductions.

Correlation between wetted area and evaporation time

Pearson correlation analysis revealed significant negative relationships between the wetted areas and evaporation time across all solutions and wheat surfaces (Fig. 10), indicating that increased spreading consistently accelerated drying. MSO, NIS, and OSB exhibited the strongest negative correlations (approaching a value of -1.0), while COC showed a weaker response.

Among target structures, the stem and head displayed the most pronounced negative correlations, where enhanced spreading translated directly into faster evaporation. Conversely, leaf surfaces (adaxial and abaxial) exhibited weaker correlations, reflecting their higher variability.

Discussion

Wetted area dynamics

MSO and NIS effectively increased the wetted area on wheat by overcoming its superhydrophobic barrier of micro/nanostructures and epicuticular waxes (Liu 2004; Song *et al.* 2022). Mechanistically, NIS lowers surface tension and contact angle (Xu *et al.* 2011), whereas MSO disrupts the wax layer, enabling closer epidermal contact (Basu *et al.* 2002; Xu *et al.* 2011). Consistent with soybean studies (Gimenes *et al.* 2013), MSO outperformed COC in spreading, suggesting that its paraffinic base penetrates wheat waxes less efficiently than vegetable-derived oils.

Beyond adjuvant chemistry, surface morphology governed deposition. Head and adaxial leaf surfaces efficiently transitioned to a spreading state once surface tension dropped below a critical threshold (Jiang *et al.* 2024; Ma *et al.* 2024). Conversely, spreading resistance on stem and abaxial surfaces likely resulted from dense trichomes or persistent waxes trapping air pockets, preventing direct tissue contact (Xu *et al.* 2011; Precipito *et al.* 2018; Makhnenko *et al.* 2025).

The quadratic concentration-response patterns highlighted a non-linear relationship between adjuvant dose and wetted area. Optimal concentrations exist beyond which further additions yield no significant spreading gains and instead risk droplet run-off (Yu *et al.* 2009; Gimenes *et al.* 2013). This saturation effect confirms that exceeding the maximum retention

capacity of difficult-to-wet surfaces through excessive surface tension reduction triggers dynamic instability and product loss (Yu *et al.* 2009; Ma *et al.* 2022).

Evaporation kinetics

Enhanced spreading inherently accelerates droplet drying on wheat. Water-only droplets remain in a Cassie-Baxter state on superhydrophobic surfaces, where air trapped in wax micro/nanostructures restricts vapor diffusion. Conversely, adjuvants promote a transition to the Wenzel state, eliminating air pockets and accelerating evaporation through closer epidermal contact (Zhou *et al.* 2018).

Although oil-based adjuvants enhance spreading and adhesion, they do not effectively reduce post-deposition evaporation (Zhu and Lin 2016). Adjuvant-amended droplets form wider, thinner liquid films than water-only droplets of the same size (Fig. 6). Because adjuvant concentrations were $\leq 2.00\%$ (Table 1), these thin, highly aqueous films evaporated faster. The expanded air-liquid interface accelerates heat and mass transfer to the surrounding environment, overwhelming any evaporation-retarding effects of the small oil portion (Gimenes *et al.* 2013; Oliveira *et al.* 2019; Wang *et al.* 2022). Furthermore, COC maintained longer evaporation times than MSO or NIS, confirming that paraffinic petroleum-based oils disrupt waxy barriers and spread less efficiently than vegetable-derived oils (Xu *et al.* 2011).

Trade-offs between spreading and evaporation

A strong negative correlation confirmed the thermodynamic interdependence of droplet spreading and drying. Superior spreaders (MSO, NIS, OSB) expanded the liquid-air interface into thinner films, accelerating evaporation. Furthermore, head and stem microtopographies were highly sensitive to surface tension reductions, modulating this coupled dynamic.

This highlights a critical agronomic trade-off: excessive spreading exceeds carrying capacity, causing run-off. Moreover, rapid evaporation triggers premature pesticide crystallization, making deposits susceptible to physical removal (Gaskin *et al.* 2000; Song *et al.* 2022; Meng *et al.* 2023). Conversely, slow-drying droplets enhance absorption but risk poor retention on vertical wheat structures.

Optimizing applications requires balancing extensive coverage with sufficient droplet longevity through precise adjuvant selection and dosing (Yu *et al.* 2009). Future studies must validate these laboratory findings under dynamic field conditions, accounting for canopy turbulence and fluctuating humidity.

Conclusions

Adjuvant chemistry and concentration govern droplet spreading on wheat heads and stems, which are the critical, vertically oriented targets for disease management. A fundamental thermodynamic trade-off emerged: overcoming wheat's superhydrophobicity maximized wetted areas but inherently accelerated evaporation. This dynamic was highly sensitive on the textured microtopography of the head and stem, where wetting created thinner liquid films and faster drying than on flatter flag leaves.

MSO and NIS were the most effective classes for enhancing droplet spreading, consistently outperforming COC across all wheat structures. Because these interactions are dose-dependent and surface-specific, no universal optimal concentration exists. Practically, doses must be calibrated to balance extensive coverage with sufficient drying time, preventing premature pesticide crystallization and optimizing systemic delivery. Future research must validate these thermodynamic trade-offs under dynamic field conditions, incorporating canopy microclimates, specific active ingredients, and diverse wheat cultivars (beyond 'Hopewell') to confirm broad generalizability.

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References

- Alisaac E, Mahlein AK. 2023. Fusarium Head Blight on Wheat: Biology, Modern Detection and Diagnosis and Integrated Disease Management. *Toxins* (Basel). 15(3). DOI: <https://doi.org/10.3390/toxins15030192>
- Basu S, Luthra J, Nigam KDP. 2002. The effects of surfactants on adhesion, spreading, and retention of herbicide droplet on the surface of the leaves and seeds. *Journal of Environmental Science and Health, Part B*. 37(4):331–344.
- Figueroa, M., Hammond-Kosack, K. E., & Solomon, P. S. (2018). A review of wheat diseases—a field perspective. In *Molecular Plant Pathology* (Vol. 19, Number 6, pp. 1523–1536). Blackwell Publishing Ltd. DOI: <https://doi.org/10.1111/mpp.12618>
- Gaskin RE, Murray RJ, Krishna H, Carpenter A. 2000. Effect of adjuvants on the retention of insecticide spray on cucumber and pea foliage. *New Zealand Plant Protection* [Internet]. 53:355–359. http://www.nzpps.org/terms_of_use.html
- Gimenes MJ, Zhu H, Raetano CG, Oliveira RB. 2013. Dispersion and evaporation of droplets amended with adjuvants on soybeans. *Crop Protection*. 44:84–90. DOI: <https://doi.org/10.1016/j.cropro.2012.10.022>
- Jiang Y, Yang Z, Xu X, Ma L, Xie B, Yu J, Duan J. 2024. Regulation mechanism of droplets wetting on banana leaf surface and its dynamic contact angle wetting model. *Crop Protection*. 186. DOI: <https://doi.org/10.1016/j.cropro.2024.106920>
- Jørgensen LN, Kudsk P, Ørum JE. 2019. Links between pesticide use pattern and crop production in Denmark with special reference to winter wheat. *Crop Protection*. 119:147–157. DOI: <https://doi.org/10.1016/j.cropro.2019.01.024>
- Liu Z. 2004. Effects of surfactants on foliar uptake of herbicides - A complex scenario. *Colloids and Surfaces B: Biointerfaces*. 35(3–4):149–153. DOI: <https://doi.org/10.1016/j.colsurfb.2004.02.016>
- Ma J, Liu K, Dong X, Chen C, Qiu B, Zhang S. 2022. Effects of Leaf Surface Roughness and Contact Angle on In Vivo Measurement of Droplet Retention. *Agronomy*. 12(9).DOI: <https://doi.org/10.3390/agronomy12092228>
- Ma X, Chen Y, Song Y, Liu M, Cao L, Pengyue Z, Huang Q, Cao C. 2024. Machine learning-based screening of pesticide adjuvants for reduction of pesticide losses on wheat leaf surfaces. *New Plant Protection*. 1(2). DOI: <https://doi.org/10.1002/npp2.16>
- Makhnenko I, Hoerning C, Sawall DD, Fredericks SA, Alonzi ER, Dutcher CS. 2025. Evaporation, spreading, and possible uptake of droplets on sorghum (*Sorghum bicolor*)

- and cowpea (*Vigna unguiculata*) leaves using an imaging-based technology. *Pest Management Science*. 81(2):884–891. DOI: <https://doi.org/10.1002/ps.8491>
- Meng Y., Liu X., Wu Q., Chen W.H., Chen W., Zhang Y., Du X., Han Y. 2025. Comprehensive Study on the Effects of Peanut Leaf Characteristics and Tank-Mix Adjuvant on Droplet-Spreading Behavior. *ACS Omega*. 10(12):11994–12001. DOI: <https://doi.org/10.1021/acsomega.4c09553>
- Meng Y, Wu Q, Zhou H, Hu H. 2023. How tank-mix adjuvant type and concentration influence the contact angle on wheat leaf surface. *PeerJ*. 11. DOI: <https://doi.org/10.7717/peerj.16464>
- Oliveira RB, Bonadio Precipito LM, Gandolfo MA, de Oliveira JV, Lucio FR. 2019. Effect of droplet size and leaf surface on retention of 2,4-D formulations. *Crop Protection*. 119:97–101. DOI: <https://doi.org/10.1016/j.cropro.2019.01.015>
- Precipito LMB, Dario G, Oliveira J V., Oliveira RB. 2018. Evaporation and wettability of fungicide spray, with or without adjuvant, on leaves of vegetables. *Horticultura Brasileira*. 36(3):320–324. DOI: <https://doi.org/10.1590/s0102-053620180306>
- R Core Team. 2022. R: A Language and Environment for Statistical Computing.
- Singh J, Chhabra B, Raza A, Yang SH, Sandhu KS. 2023. Important wheat diseases in the US and their management in the 21st century. *Frontiers in Plant Science*. 13. DOI: <https://doi.org/10.3389/fpls.2022.1010191>
- Song Y, Huang Q, Huang G, Liu M, Cao L, Li F, Zhao P, Cao C. 2022. The Effects of Adjuvants on the Wetting and Deposition of Insecticide Solutions on Hydrophobic Wheat Leaves. *Agronomy*. 12(9). DOI: <https://doi.org/10.3390/agronomy12092148>
- Wang G, Ou M, Jia W, Zhou H, Dai S, Dong X, Wang X, Jiang L, Lu W, Wang M. 2022. The Dynamic Evaporation Characteristics of Thiophanate-Methyl Droplets and Their Enhancement under Different Wind Conditions. *Horticulturae*. 8(8). DOI: <https://doi.org/10.3390/horticulturae8080721>
- Xu L, Zhu H, Ozkan HE, Bagley WE, Krause CR. 2011. Droplet evaporation and spread on waxy and hairy leaves associated with type and concentration of adjuvants. *Pest Management Science*. 67(7):842–851. DOI: <https://doi.org/10.1002/ps.2122>
- Yan X, Wang M, Zhu Y, Shi X, Liu X, Chen Y, Xu J, Yang D, Yuan H. 2021. Effect of aviation spray adjuvant on improving control of fusarium head blight and reducing mycotoxin contamination in wheat. *Agriculture (Switzerland)*. 11(12). DOI: <https://doi.org/10.3390/agriculture11121284>

- Yu Y, Zhu H, Ozkan HE, Derksen RC, Krause CR. 2009. Evaporation and deposition coverage area of droplets containing insecticides and spray additives on hydrophilic, hydrophobic, and crabapple leaf surfaces. *Transactions of the ASABE*. 52(1):39–49.
- Zhou Z, Cao C, Cao L, Zheng L, Xu J, Li F, Huang Q. 2018. Effect of surfactant concentration on the evaporation of droplets on cotton (*Gossypium hirsutum* L.) leaves. *Colloids and Surfaces B: Biointerfaces*. 167:206–212. DOI: <https://doi.org/10.1016/j.colsurfb.2018.04.018>
- Zhu H., Lin, J. 2016. Coverage Area and Fading Time of Surfactant-Amended Herbicidal Droplets on Cucurbitaceous Leaves. *Transactions of the ASABE*. 59(3): 829-838. 10.13031/trans.59.11427
- Zhu H, Yu Y, Ozkan HE, Derksen RC, Krause CR. 2008. Influence of spray additives on droplet evaporation and residual patterns on wax and wax-free surfaces Written for presentation at the 2008 ASABE Annual International Meeting Sponsored by ASABE Rhode Island Convention Center Providence, Rhode Island. 2008 ASABE Annual International Meeting (ASABE Paper No 083752).

Table 1. Concentration and surface tension of adjuvant-water solutions at five relative concentrations used for the test.

Adjuvants	Chemical composition	Concentration (% v/v)	Relative Concentration (RC)	Surface tension (mN m ⁻¹)
Crop Oil Concentrate (COC)	Paraffin base petroleum oil 83%; surfactant blend 17%	0.26	0.25	38.1
		0.52	0.50	36.5
		1.04	1.00	36.2
		1.56	1.50	35.8
		2.08	2.00	35.8
Modified Seed Oil (MSO)	Methyl soyate, nonyphenol ethoxylate blend (surfactant content 15%)	0.13	0.25	35.9
		0.26	0.50	35.0
		0.52	1.00	34.8
		0.79	1.50	34.8
		1.04	2.00	34.7
Nonionic Surfactant (NIS)	Alkylphenol ethoxylat, butyl alcohol, dimethylpolysiloxane 90%; Constituents, Ineffective as Spray Adjuvant 10%	0.06	0.25	30.7
		0.13	0.50	29.6
		0.25	1.00	28.8
		0.38	1.50	29.2
		0.50	2.00	31.2
Oil Surfactant Blend (OSB)	Ethylated seed oil; 3-(3- hydroxypropyl)- heptamethyltrisiloxane, ethoxylated acetate; polyoxyethylene dioleate; polyol alkyl thoxylate (surfactant content 40%)	0.03	0.25	33.7
		0.06	0.50	32.1
		0.13	1.00	31.4
		0.19	1.50	30.6
		0.26	2.00	30.8
Water – only	-	-	-	72.2

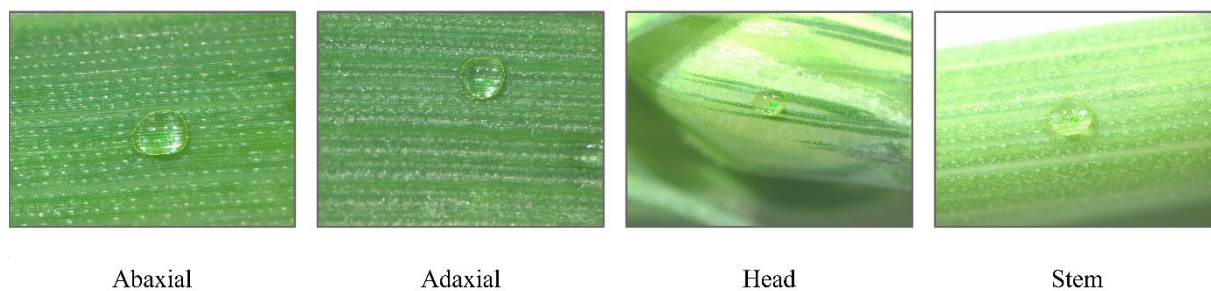


Figure 1. Images of water-only droplets deposited at four locations on wheat leaves.

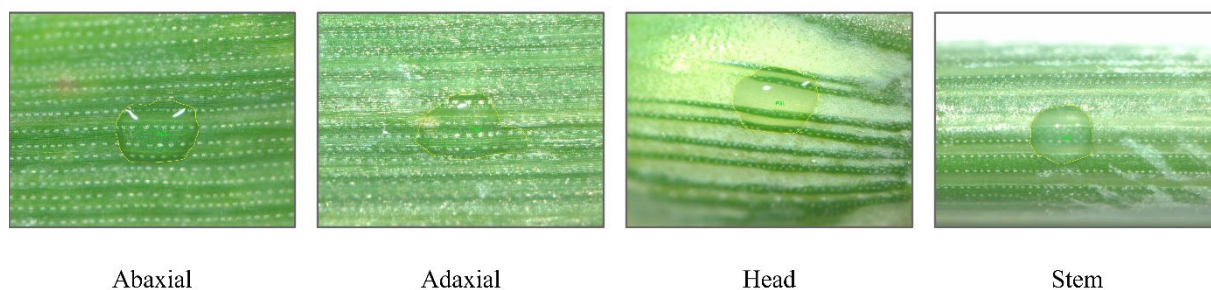


Figure 2. Images of droplet deposit patterns at four locations with MSO at the manufacturer's relative concentration ($RC = 1.00$).

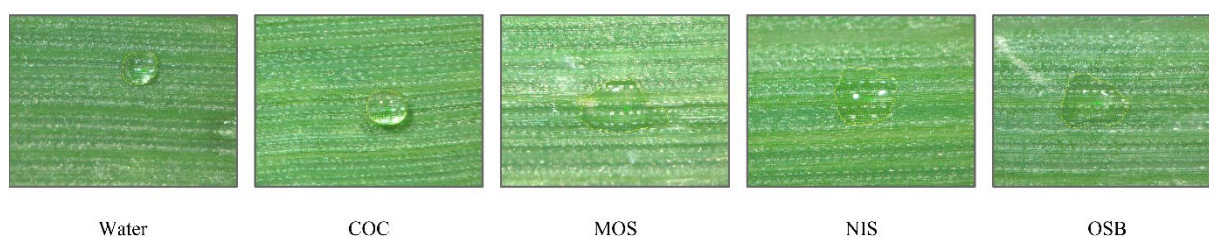


Figure 3. Final dispersion of 300 μm droplet on the adaxial surface of wheat leaves during the spread and evaporation processes with water, and adjuvants of COC, MSO, NIS and OSB at the manufacturer's relative concentration (RC = 1.00).

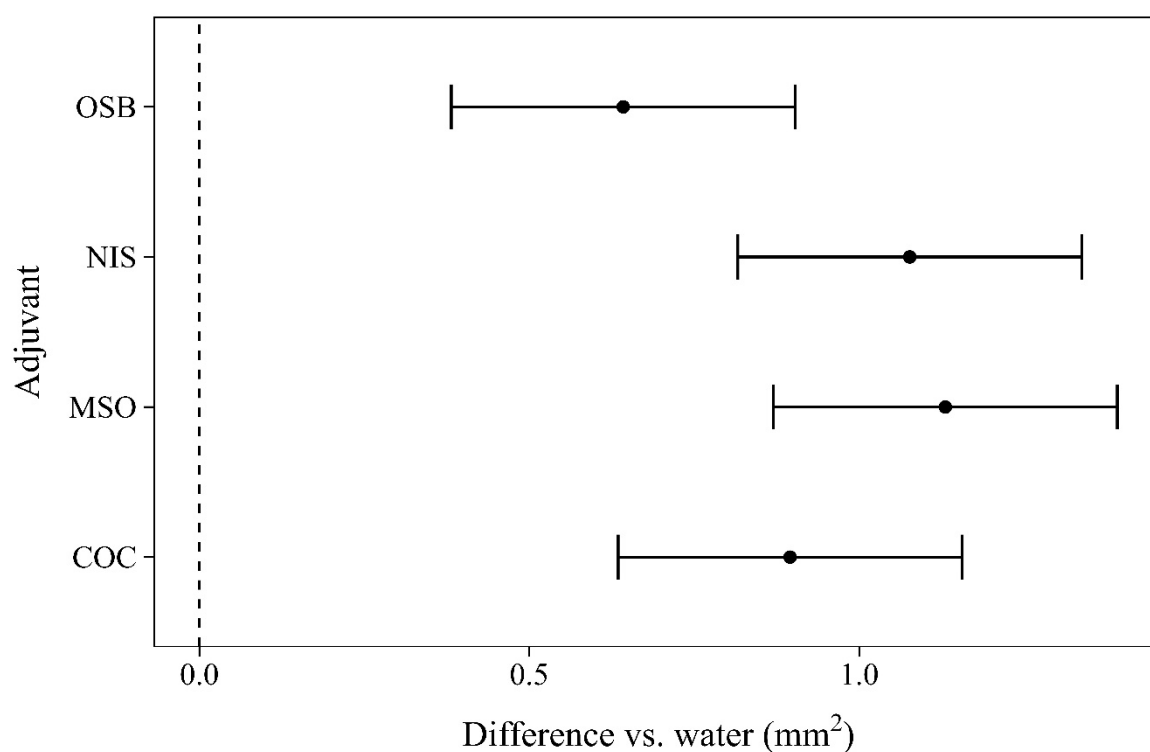


Figure 4. Mean differences in droplet wetted areas between adjuvants (COC, MSO, NIS, OSB) and water control across wheat structures. The dashed zero-line represents the water baseline; positive values indicate enhanced spreading. Confidence intervals (Dunnett's test) entirely above zero confirm statistically significant spreading increases for all adjuvants compared to water.

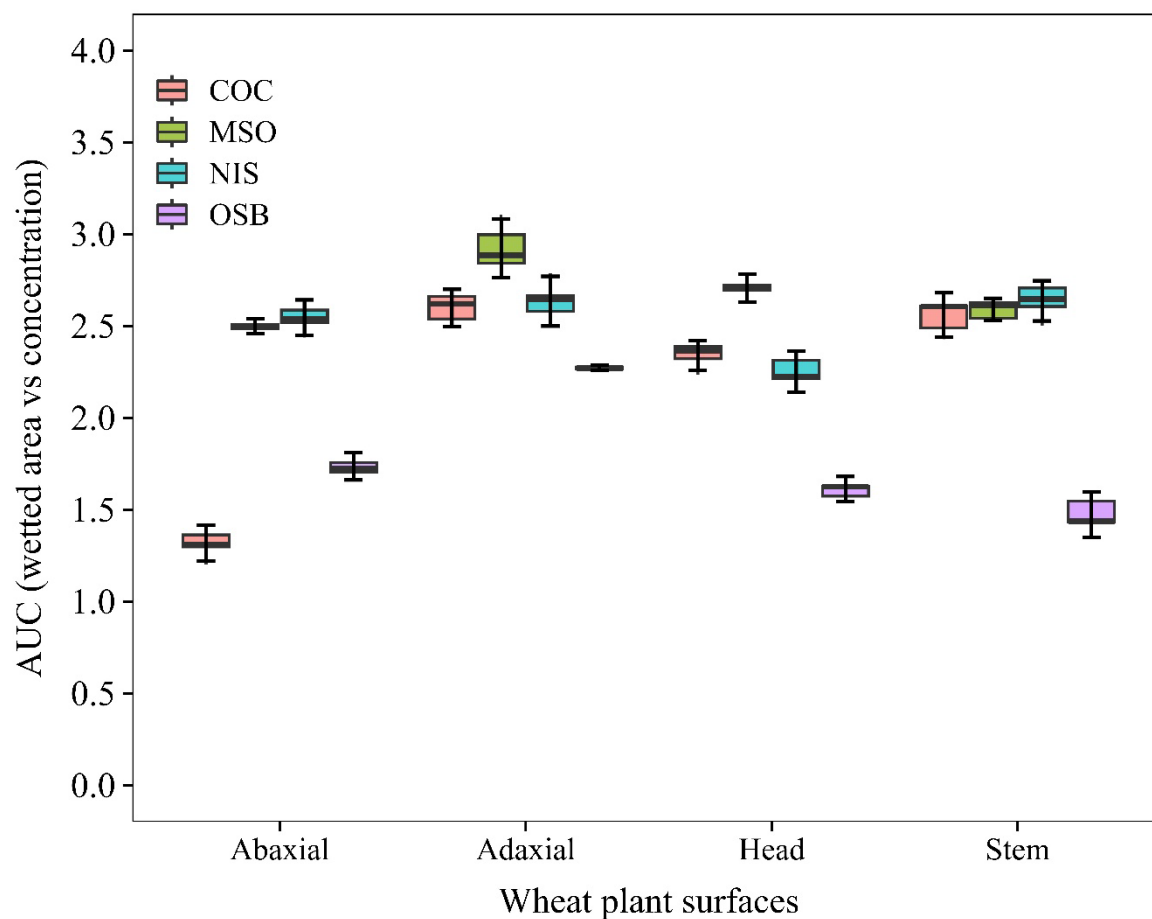


Figure 5. Area Under the Curve (AUC) for droplet wetted areas across adjuvant concentrations (0.25–2.00% v/v) on wheat surfaces. AUC summarizes the cumulative spreading response, where higher values indicate greater wettability and adjuvant responsiveness. Adjuvants: crop oil concentrate (COC), modified seed oil (MSO), non-ionic surfactant (NIS), oil surfactant blend (OSB). Surfaces: adaxial/abaxial leaves, stem, head. Boxes show interquartile ranges and medians; whiskers denote min/max values (n = 5).

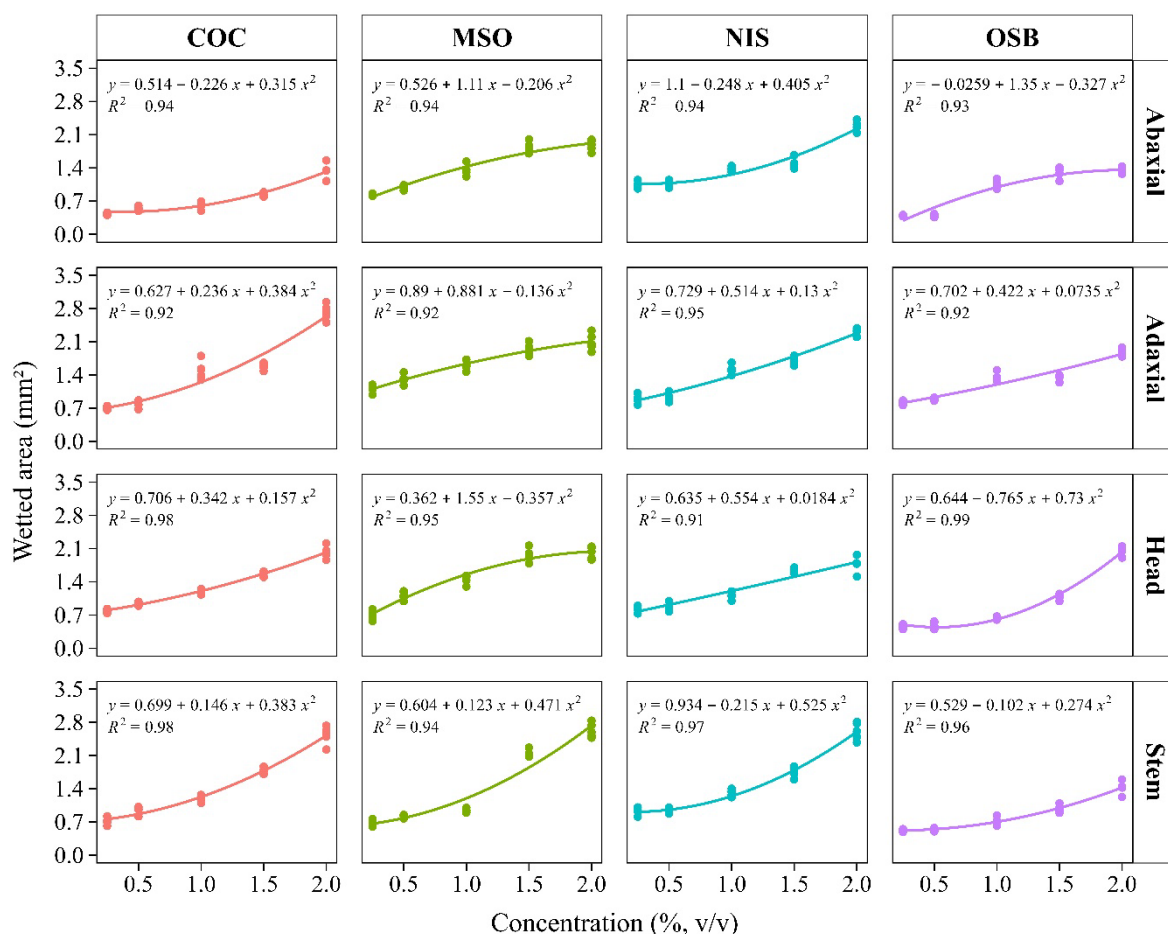


Figure 6. Concentration-response of wetted areas across wheat surfaces and adjuvants. Points show experimental data ($n = 5$); solid lines represent quadratic regressions ($y = ax^2 + bx + c$). Dashed lines indicate the water-only baseline for each surface. Regression equations and R^2 values are displayed within panels. Adjuvants: crop oil concentrate (COC), modified seed oil (MSO), non-ionic surfactant (NIS), oil surfactant blend (OSB).

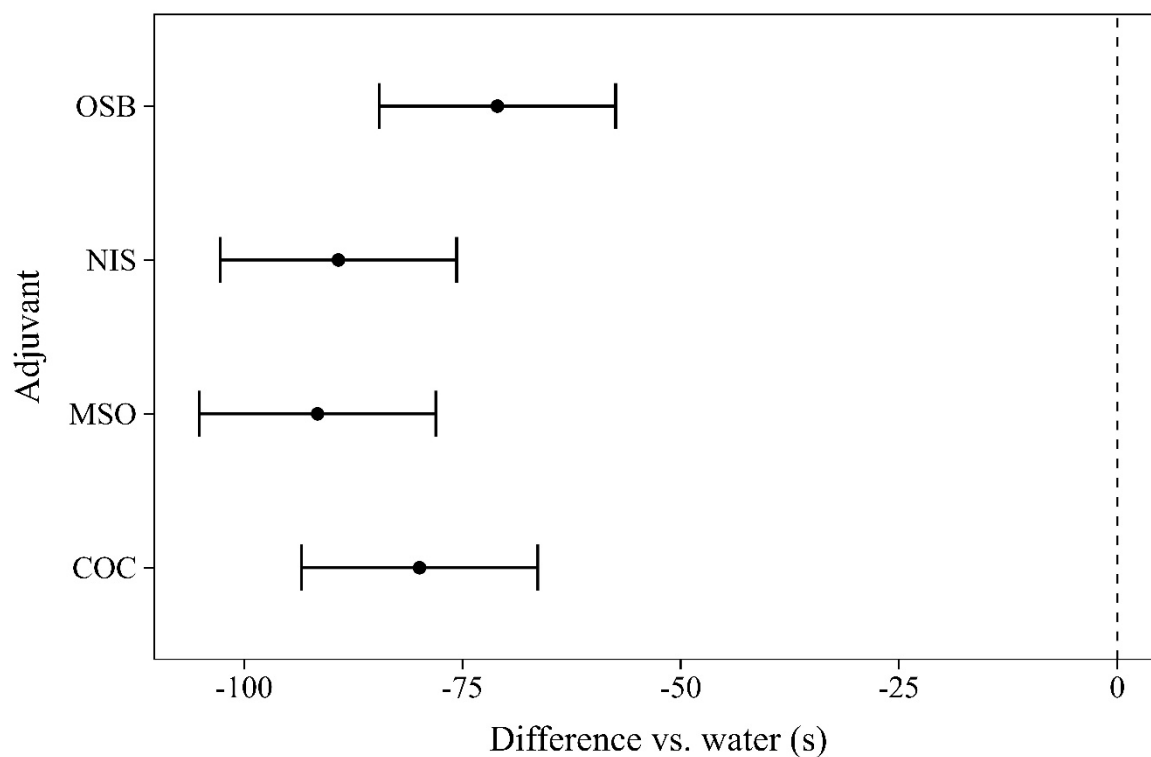


Figure 7. Mean differences in droplet evaporation time between adjuvants (COC, MSO, NIS, OSB) and water control across wheat structures. The dashed zero-line represents the water baseline; negative values indicate faster drying. Confidence intervals (Dunnett's test) entirely below zero confirm statistically significant evaporation acceleration for all adjuvants compared to water.

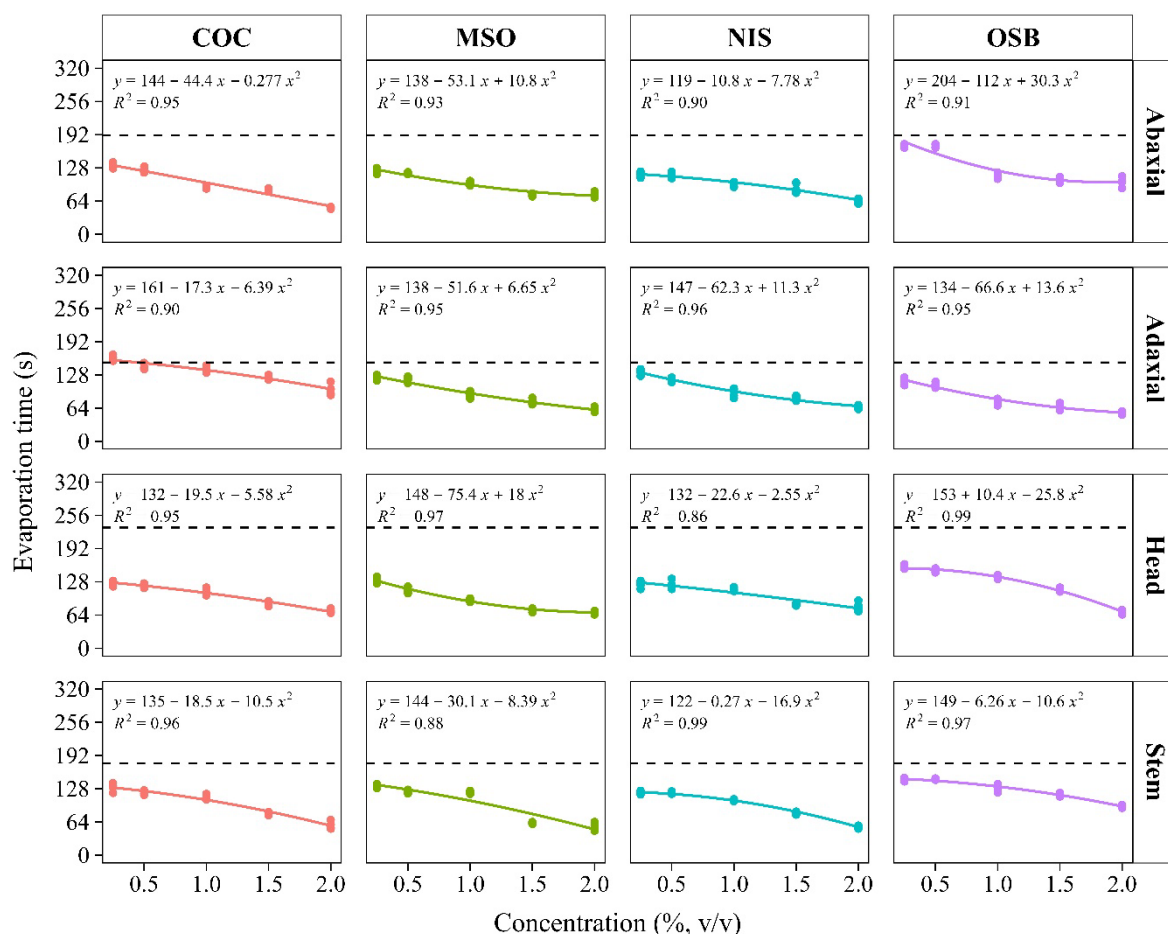


Figure 8. Concentration-response of droplet evaporation time across wheat surfaces and adjuvants. Points show experimental data ($n = 5$); solid lines represent regression models (linear or quadratic). Dashed lines indicate the water-only baseline for each surface. Regression equations and R^2 values are displayed within panels. Downward slopes indicate accelerated drying at higher concentrations. Adjuvants: crop oil concentrate (COC), modified seed oil (MSO), non-ionic surfactant (NIS), oil surfactant blend (OSB).

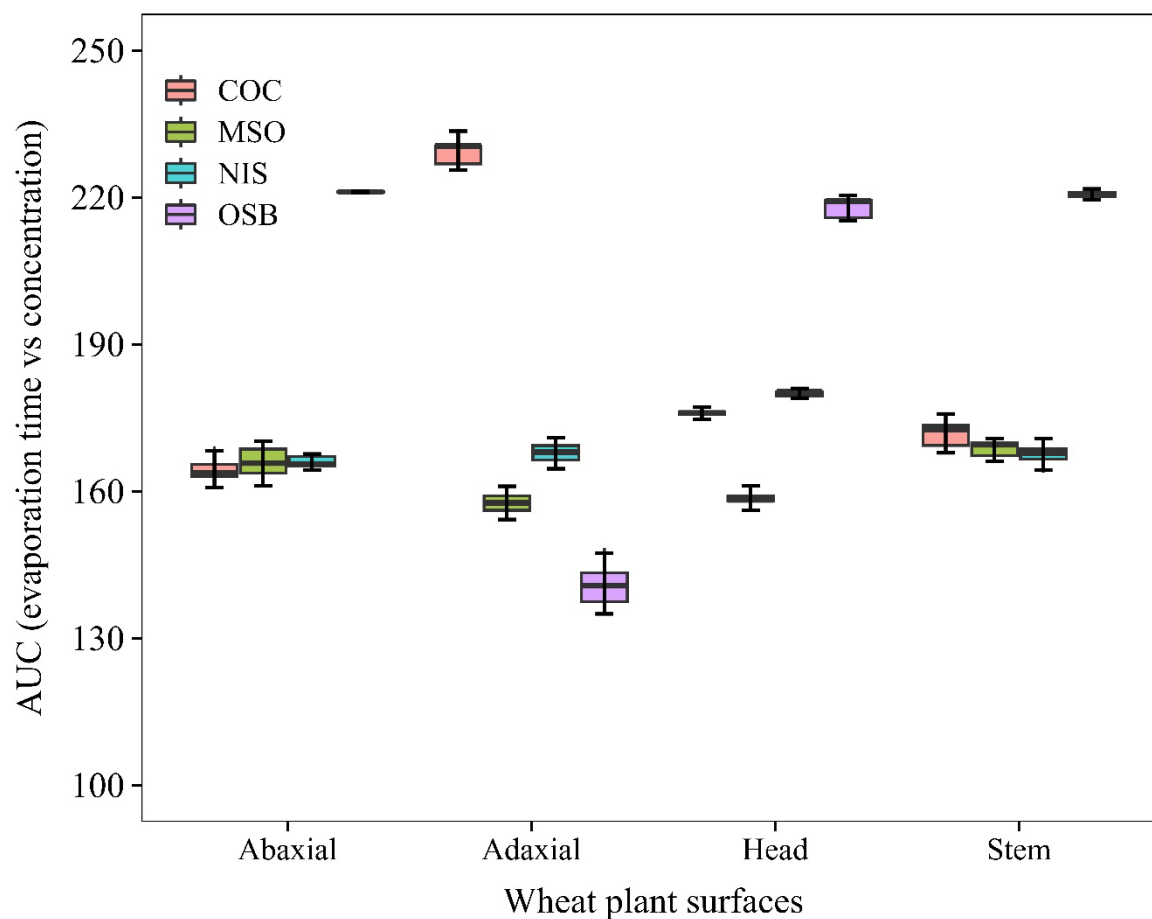


Figure 9. Area Under the Curve (AUC) for droplet evaporation time across adjuvant concentrations (0.25–2.00% v/v) on wheat surfaces. AUC summarizes the cumulative dose-response, where lower values indicate faster overall evaporation. Adjuvants: crop oil concentrate (COC), modified seed oil (MSO), non-ionic surfactant (NIS), oil surfactant blend (OSB). Surfaces: adaxial/abaxial leaves, stem, head. Boxes show interquartile ranges and medians; whiskers denote min/max values (n = 5).

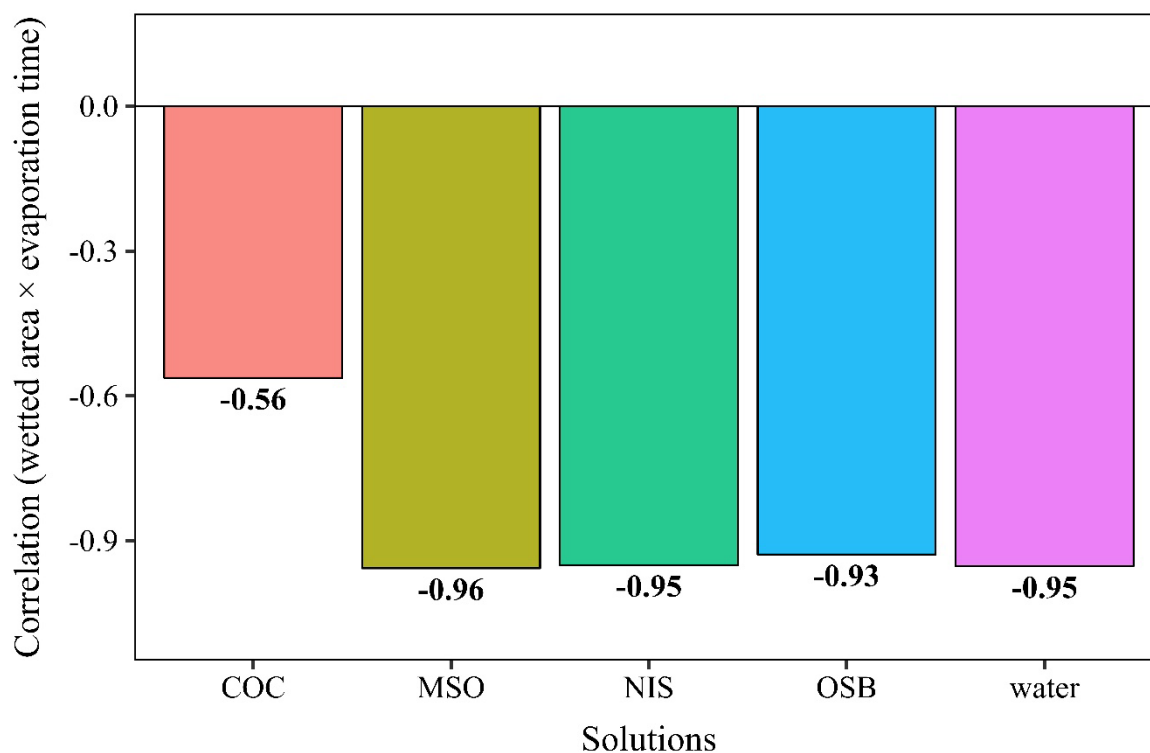


Figure 10. Pearson correlation coefficients between wetted areas (mm^2) and evaporation time (s) across adjuvants and wheat surfaces. Values approaching -1.0 indicate that increased spreading strongly accelerated evaporation. All displayed correlations are significant ($p < 0.05$). Adjuvants: crop oil concentrate (COC), modified seed oil (MSO), non-ionic surfactant (NIS), oil surfactant blend (OSB). Surfaces: adaxial/abaxial leaves, stem, head. Note the highly responsive head and stem compared to variable leaf surfaces.